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Impact of biofilm on bacterial transport and deposition in porous media

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ABSTRACT

Laboratory scale experiments were conducted to obtain insights into factors that influence bacterial transport and deposition in porous media. According to colloidal filtration theory, the removal efficiency of a filter medium is characterized by two main factors: collision efficiency and sticking efficiency. In the case of bacterial transport in porous media, bacteria attached to a solid surface can establish a thin layer of biofilm by excreting extracellular polymeric substances which can significantly influence both of these factors in a porous medium, and thus, affect the overall removal efficiency of the filter medium. However, such polymeric interactions in bacterial adhesion are not well understood and a method to calculate polymeric interactions is not yet available. Here, to determine how the migration of bacteria flowing within a porous medium is affected by the presence of surface-associated extracellular polymeric substances previously produced and deposited by the same bacterial species, a commonly used colloidal filtration model was applied to study transport and deposition of *Pseudomonas fluorescens* in small-scale columns packed with clean and biofilm coated glass beads. Bacterial recoveries were monitored in column effluents and used to quantify biofilm interactions and sticking efficiencies of the biofilm coated packed-beds. The results indicated that, under identical hydraulic conditions, the sticking efficiencies in packed-beds were improved consistently by 36% when covered by biofilm.

1. Introduction

Found virtually in all moist environments, biofilms are the most dominant form of bacterial growth in natural and engineered systems (Rittamann, 1990). The formation of a bacterial biofilm starts when planktonic bacteria attach to a solid surface in an aqueous environment (Fig. 1A). Subsequent division of attached cells coupled with simultaneous secretion of adhesive extracellular polymeric substances (EPSs) generate a thin biofilm layer on the solid surface. Further cell proliferation and EPS production results in biofilm growth and maturation (van Loosdrecht et al., 1990). In porous structures, the presence of biofilm on the inner surface of the solid matrix can significantly affect bacterial transport and deposition by modifying either geohydrological properties or physicochemical surface characteristics (Rittamann, 1990).

Bacterial deposition in porous media is a crucial phenomenon in different environmental and industrial applications, including protection of groundwater from pathogen migration (Abuashour et al., 1994), in situ subsurface bioremediation (Gross and Logan, 1995), water and wastewater treatment (Davis et al., 2007; Waybrant et al., 1998), and biofiltration (Devinny and Ramesh, 2005; Harvey and Garabedian, 1991). Therefore, performance and efficiency of such processes can be influenced by formation, growth, and maturation of bacterial biofilm.

However, whereas there are numerous biofilm-based applications already in use, there is a lack of mechanistic understanding of processes that affect transport and deposition behavior of bacteria in biofilm-coated granular porous media. Available theories are arguably incomplete and evaluations of

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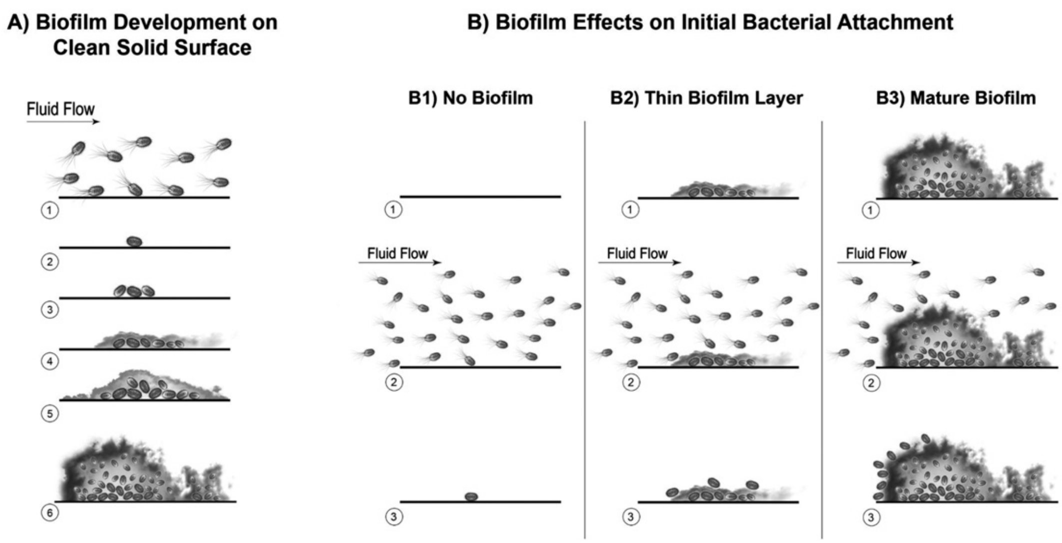

Fig. 1. (A) Stages of bacterial biofilm development on a clean surface: 1) planktonic bacterial cells contact the solid surface; 2) some bacteria may reversibly attach to the solid surface based on the contact angle and surface properties; 3) reversibly attached bacteria grow and proliferate through cell duplication in the presence of sufficient nutrients; 4) bacterial attachment becomes irreversible due to secretion of EPS which results in the formation of a thin layer of biofilm; 5) preliminary steps of biofilm maturation by initiating development of three-dimensional biofilm structure; and 6) fully mature biofilm as indicated by the complex biofilm structure and architecture. (B) How the presence of EPS on solid surfaces may be able to enhance bacterial attachment. Compared to no biofilm present (B1), a thin biofilm layer (B2) changes solid surface physicochemical properties that promote cell attachment, and the increased surface area of a mature biofilm (B3) can further enhance bacterial deposition (reducing available pore space in the process).

such theoretical models against laboratory or field experimental data are few (Katsikogianni and Missirlis, 2004). A full understanding of bacterial adhesion under the particular physical, geochemical, and biological conditions found in a given porous medium is required to improve the efficiency of existing biofilm-based processes, and to design and implement new field scale applications.

As bacteria can be considered to be colloidal particles, classical colloid filtration theory (CFT) has been used extensively to study bacterial transport and deposition in porous media (Harvey and Garabedian, 1991; Li and Logan, 1999; Yao et al., 1971). Once a particle strikes a collector surface, a balance between the drag force drawing colloidal particles towards the collector and attractive/repulsive forces at solid interface determines whether or not the particle will adhere. However, properties of the interacting surfaces are not included in CFT and adhesion of colloidal particles to a solid surface is only controlled by mass transfer of suspended particles from the bulk flow to the surface of the grains (i.e. collectors) that make up a porous medium (Li and Logan, 1999; Yao et al., 1971). To include surface properties, DLVO theory (named after Derjaguin, Landau, Verwey and Overbeek) has been developed to describe short-range interactions between a striking particle and collector solid surface by considering attractive van der Waals and generally repulsive electrostatic forces (Derjaguin and Landau, 1941; Rutter and Vincent, 1980). Nonetheless, as DLVO theory focuses on only one of several mechanisms of the adhesion process and ignores the various molecular interactions that occur when polymeric substances are present on a collector surface, the application of DLVO-type theories has not been always successful for the elucidation of diverse bacterial attachment behaviors in biological processes (Azeredo et al., 1999; Parent and Velegol, 2004). Based on DLVO theory, bacteria, as colloidal particles with smooth rigid surfaces, adhere when they are close enough to a surface to overcome electrostatic repulsive forces. Also, it is assumed that collector and colloidal particles surface properties are invariant throughout the filtration process (Harvey and Garabedian, 1991). Obviously, such assumptions cannot explain various molecular interactions influencing bacterial adhesion, especially when bacterial surface exopolymers interact with macromolecular groups on collector surfaces, and thus, interfere with DLVO type interactions (Camesano and Logan, 2000; Ong et al., 1999).

It has been postulated that bacterial adhesion to solid surfaces is related to the adsorption of outer membrane polymers to solid surfaces (Burks et al., 2003; Lytle et al., 2002). Most bacteria are able to produce polymeric compounds which remain associated with the cell wall, or be secreted into the medium (Decho et al., 2005). The higher affinity of such exopolymers to the surface compared to the aqueous phase facilitates bacterial adhesion by two main processes: surface modification (polymer attraction between bacterial and surface polymers resulting in improved sticking efficiency) and surface enhancement (occupying higher portion of available void space to floating cells leading to higher collision efficiency) (Fig. 1B). Therefore, unlike colloidal filtration, bacteria removal in porous media should be considered as an evolving process in which intrinsic collector properties in the filter medium change following bacterial adhesion and EPS secretion.

The presence of biofilm EPS may change porous media physicochemical surface characteristics, thereby altering hydrophobicity, electrostatic, and van der Waals interactions between bacteria and porous media surfaces (Elimelech et al., 1995; Walker et al., 2004). Bacterial attachment to solid surfaces would be enhanced by increasing surface hydrophobicity due to the reduction of connate water saturation (Elimelech et al., 1995). Bacterial EPS is normally composed of variable proportions of polysaccharides, lipopolysaccharides,